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by

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Summary

A summary of the work performed under NASA grant NCC3-605 is presented. More details can be found in the cited references. This grant led to the development of relatively faster aeroelastic analysis methods for predicting flutter and forced response in fans, compressors, and turbines using computational fluid dynamic (CFD) methods. These methods are based on linearized two- and three-dimensional, unsteady, nonlinear aerodynamic equations. During the period of the grant, aeroelastic analysis that includes the effects of uncertainties in the design variables has also been developed.

Linearized Euler solvers

Previous aeroelastic analyses were performed by using the unsteady aerodynamic equations based on uniform flow. These methods neglected the effects of steady aerodynamic loading on the unsteady aerodynamic forces. The steady loading is due to the angle of attack and the airfoil shape. These methods required minimum computational time for an aeroelastic analysis. Advanced methods based on computational fluid dynamic (CFD) methods have been developed to include the steady loading effects in the aeroelastic analysis. However, these methods, usually based on time marching, require considerable computational resources to performe aeroelastic analyses.

Methods based on linearized unsteady aerodynamic equations combine the benefits of the above two methods. They are faster and include steady loading effects. This is achieved by linearizing the non-linear unsteady equations on a non-linear steady aerodynamic solution to obtain linear unsteady aerodynamic equations. These equations can be solved in the frequency domain, by assuming harmonic motion for the unsteady oscillations. The resulting analysis code is very efficient and includes steady loading effects. Over the duration of the grant aeroelastic analysis codes have been developed using a 2D linearized Euler solver, LINFLUX-2D, and a 3D linearized Euler solver LINFLUX-3D. The difference between the codes is associated with the different structural models employed

During the period of the grant, a version of the LINFLUX-2D code and a version of the LINFLUX-3D code were implemented on an SGI machine, and the results of unsteady

aerodynamic calculations were compared with published results. The execution of LINFLUX-3D required learning and running a steady aerodynamic code, i.e., the TURBO-AE code on an SGI machine. This, in turn, required the development of an interface code to link the steady solution from the TURBO-AE code to the LINFLUX-3D code.

Two-Dimensional Aeroelastic Analysis code MISER-LE

A typical section structural model was used to develop the aeroelastic code, MISER-LE. The unsteady aerodynamic forces were obtained from the linearized Euler solver, LINFLUX-2D. This structural model has two degrees of freedom: bending and torsion. The governing aeroelastic equations are solved in the frequency domain for each interblade phase angle. Two cascades, one with 9 blades and the other with 12 blades, were analyzed. The unsteady aerodynamic forces were obtained from a linear theory, where steady loading effects were neglected, and from LINFLUX-2D where they were included. The flutter results are presented in Ref. 1. An extended version of this paper, showing extension to forced response as well as a correlation with previously published data is given Ref. 2.

Quasi-3D Aeroelastic Analysis code, ASTROP2-LE

In this analysis, a three-dimensional structural model was used for the aeroelastic analysis. The unsteady aerodynamic forces were obtained from LINFLUX-2D. The structural and the unsteady aerodynamic models were combined using strip theory. An existing code, ASTROP2, was updated to include forced response, and the unsteady aerodynamic solution from LINFLUX-2D. The governing equations were solved in the frequency domain. The details regarding the resulting code, ASTROP2-LE, and the numerical aeroelastic results for a tuned cascade were presented in Ref. 3. The study was later extended to include mistuning effects and was published as a NASA TM, Ref. 4.

Three-Dimensional Aeroelastic Analysis code, LINFLUX-AE

In this portion of the research, an aeroelastic system, LINFLUX-AE, was developed for the aeroelastic analysis of three-dimensional structures with three-dimensional aerodynamic analysis. A three-dimensional structural model was combined with the three-dimensional unsteady aerodynamic model, LINFLUX-3D. A normal mode approach combined with the frequency domain solution method was used in the aeroelastic analysis. Modules were developed to interpolate structural mode shapes on aerodynamic grids, calculation of generalized forces and flutter eigenvalues. The modules were contrasted to known results. The details of the preliminary version of the LINFLUX-AE code were presented in Ref. 5. The paper presents flutter calculations for a helical fan with flat plate geometry, and for a real fan: the E-cubed fan.

Flutter eigenvalues and work done per cycle were compared with those obtained using TURBO-AE. The forced response predictions for the helical fan subjected to acoustic loading were presented in Ref. 6. The calculations from LINFLUX-AE were compared with those obtained from a code based on the linear aerodynamic equations in Ref. 6. A finite element model was created using ANSYS, giving realistic mode shapes and frequencies, and this was used in the flutter and forced response calculations. The flutter eigenvalues were compared with those obtained from ASTROP2 and the forced response amplitudes were compared with those obtained from ANSYS. These calculations were documented in Ref. 7.

Recently, LINFLUX-AE was applied to investigate the flutter behavior of a realistic fan developed under the Quiet High-Speed Fan (QHSF) program. LINFLUX-AE accurately predicted the flutter behavior of the QHSF fan. It predicted the mode, frequency and phase angle of flutter accurately. Recently, the code has been implemented on a cluster of computers, making it highly useful in a design environment.

Probabilistic Aeroelastic Analysis

The aeroelastic analysis codes available at present are used in a design loop with uncertainties accounted for by using safety factors. This approach yields overly conservative designs, thereby reducing the potential of designing higher efficiency engines. The Air Force High Cycle Fatigue Group identified uncertainties that had lead to many HCF problems. These include uncertainty in anticipating the amplitude of the excitation, identifying the vibration mode and frequency, missing a low order mode, material defects and damage due to manufacturing, and boundary attachments of blades to disks, etc.

An integration of the deterministic aeroelastic analysis methods with probabilistic analysis methods offers the potential to reduce aeroelastic problems and will provide a quantum leap toward designing safe reliable engines. Probabilistic analysis will allow for the development of a reliable engine.

A probabilistic approach was developed for the aeroelastic analysis of turbomachinery blade rows during the grant period. Blade rows with subsonic flow and blade rows with supersonic flow with subsonic leading edge were considered. To demonstrate the probabilistic approach, the flutter frequency, damping and forced response of a blade row representing a compressor geometry was considered. The analysis accounted for uncertainties in structural and aerodynamic design variables. The results were presented in the form of probabilistic density function (PDF) and sensitivity factors. Subsonic flow cascade comparisons were \made with different probabilistic distributions, probabilistic methods, and Monte-Carlo simulation. The approach showed that the probabilistic approach provides a more realistic and systematic way to assess the effect of design variables on the aeroelastic instabilities and response. The analysis results were presented in Refs. 8 and 9.

Recently, the probabilistic aeroelastic formulations have been extended to consider the uncertainties in material, and geometric properties by combining the structural analysis code, NESSUS to ASTROP2 and to FPI. To assess the accuracy of the NESSUS structures capability, the helical fan geometry, mentioned above, was analyzed for free vibration frequencies and mode shapes with NESSUS. These were compared with those obtained from ANSYS. Excellent correlation was obtained for the first two modes. The NESSUS code predicted mode shapes and frequencies that were subsequently used by ASTROP2 for aeroelastic prediction.

Review of Aeroelastic Analysis Methods for Turbomachinery

During the grant period, a review of the aeroelastic methods developed at the NASA Glenn Research Center and future directions was prepared and presented at the ISABE conference, Ref. 10.

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